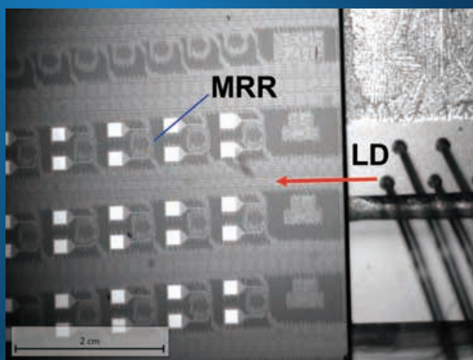
NICT NEWS
National Institute of Information and Communication Technology
No.3 2025
Vol.511

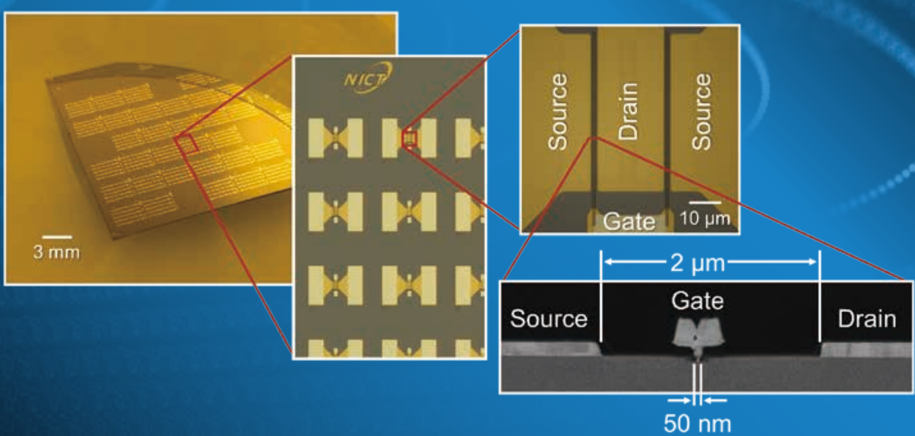
FEATURE

Terahertz Devices Pioneering the Last Frontier of Electromagnetic Waves

DIALOG

Terahertz Waves: The Final Frontier in the Electromagnetic Spectrum Between Radio Waves and Light





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National Institute of Information and Communications Technology

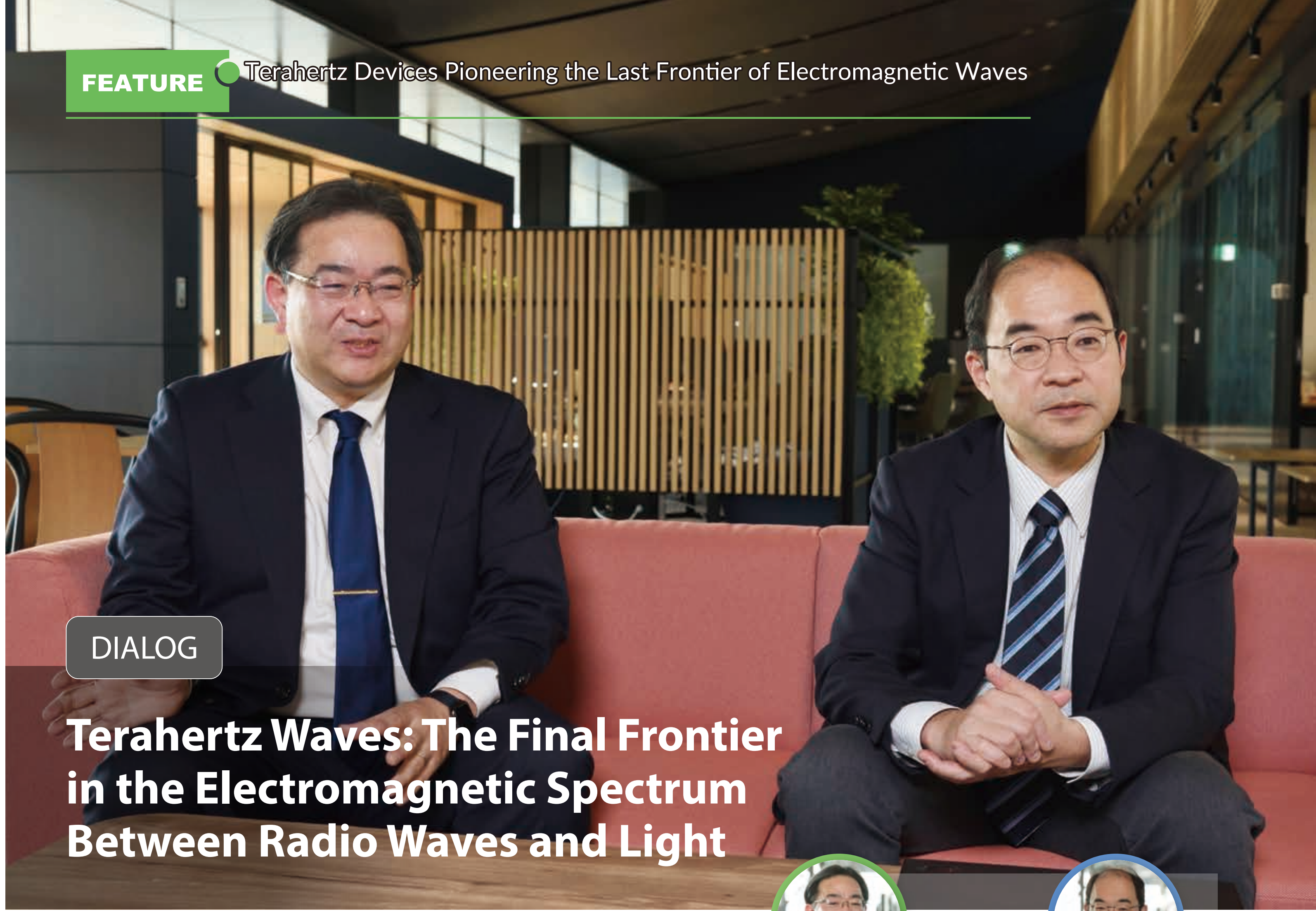
Cover Photo
Bottom Left: High electron mobility transistors (HEMTs) that operate in the terahertz band. From left, optical microscope images of a wafer after HEMT fabrication, arranged HEMTs, and HEMT electrodes, and a cross-sectional scanning electron microscope image of an enlarged view of the electrode microstructure.

Upper Right: A microscope image of a Micro Ring Resonator (MRR) that generates optical frequency combs. Direct excitation with a Laser Diode (LD) enables a compact configuration.

Photo Upper Left
Researcher Dr. MACHIDA cleaning semiconductor epi-wafers in a yellow room in a clean room facility (NICT Advanced ICT Device Laboratory) (see P4–5).

FEATURE

Terahertz Devices Pioneering the Last Frontier of Electromagnetic Waves



DIALOG

Terahertz Waves: The Final Frontier in the Electromagnetic Spectrum Between Radio Waves and Light

The history of electromagnetic wave exploration has also been a fight to achieve higher frequencies. Higher-frequency waves can transmit larger amounts of information. As such, microwaves and millimeter waves have been put to practical use to realize large-capacity wireless communications. Now, the next goal is to use terahertz waves. Terahertz waves are electromagnetic waves that have an extremely wide range of applications due to being close to light. They can be used not only for communications, but also for imaging, sensing, and measuring in applications such as body scanners.

However, terahertz waves also involve many challenges because of their high frequencies. Dr. WATANABE Issei, Director of Terahertz ICT Device Laboratory, and Dr. SEKINE Norihiko, Director of Terahertz Laboratory, who are leading the terahertz device research at NICT, shared their views.

WATANABE Issei

Director of Terahertz ICT Device Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute

After completing doctoral course, Dr. WATANABE joined NICT in 2004. He has been engaged in research on millimeter- and terahertz-wave compound semiconductor electron devices and MMICs, and high-frequency measurement technologies. He is currently a Visiting Professor at Tokyo University of Science. Ph.D. (Engineering).

SEKINE Norihiko

Director of Terahertz Laboratory, Terahertz Technology Research Center, Beyond 5G Research and Development Promotion Unit

After completing doctorial course, Dr. SEKINE worked for electric manufacturer, then for university as an assistant professor. He joined NICT in 2005. He has been engaged in research on nano level semiconductor properties in terahertz-wave and its applications. Ph.D. (Engineering).

——What are terahertz waves?

WATANABE Terahertz waves are electromagnetic waves that occupy the region between radio waves and light, at frequencies from 100 GHz to 10 THz. This range is an unexplored frequency band that has not yet been much utilized. Generally, higher-frequency waves have higher directivity and exhibit larger attenuation in the air than lower-frequency waves. Therefore, terahertz waves have different properties from those of microwaves of up to 30 GHz, such as Wi-Fi, which have been used so far. Also, as terahertz waves can convey a large amount of data due to their high frequency, they are attracting much attention from the high-speed, large-capacity wireless communications field.

SEKINE Research on terahertz waves began around the 1990s, starting from the higher-frequency optical region rather than from the radio wave region. Attention was paid to the applicability of terahertz waves in spectroscopic analysis for studying the physical properties of materials. In the 2000s, the application became possible even with the use of electron devices. Terahertz waves, which also cover the far-infrared region, have long been used in radio astronomy. Scientists captured far-infrared radiation coming from space and analyzed the elements of celestial

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bodies by spectrometry. The devices used at the time were not mass-produced, but were special, one-of-a-kind equipment for astronomical use, so they were extremely expensive.

Likewise, although millimeter wave radars that were used in research and development over 20 years ago were extremely expensive and could only be installed in luxury cars, in-vehicle radars using millimeter waves with slightly longer wavelengths than terahertz waves have become popular in recent years.

Sensing, Imaging, and Measuring

——How can terahertz waves be applied in the real world?

WATANABE Terahertz waves have even higher frequencies than conventional microwaves and millimeter waves. Therefore, in sensing and imaging, they can facilitate higher resolution, and in measuring, they make it possible to identify the substances that constitute a material and analyze their composition without destroying or making contact with the material.

Body scanners used for body checking at airport security gates use millimeter waves of about 70 to 80 GHz, which are almost the same as those of terahertz waves. If the terahertz range is used, higher resolution can be achieved, so it will become easier to detect concealed items, such as guns, as well as powder drugs and explosives. In addition, by simply placing a bottle containing a liquid in front of a terahertz scanner, we can instantly find out whether the content liquid is water or a flammable or explosive substance. In this way, we will be able to ensure stronger security by using terahertz waves.

Two Approaches

——So, terahertz waves can be used simultaneously for imaging and communications, which are seemingly different functions.

SEKINE There are two approaches to the research and development of terahertz waves. A route going from higher to lower, and a route going from lower to higher. Higher and lower refer to the frequencies. The research going from a higher range close to the frequencies of light toward the radio wave range is called "terahertz photonics," and this is what my laboratory works on. The goal of both approaches is to efficiently emit terahertz waves of the targeted frequency. The main difference is whether to use light technology or electron devices.

Our laboratory conducts research on two types of photonics technologies. One is a quantum cascade laser that emits far-infrared radiation. This technology causes a semiconductor device to directly emit a laser beam in the terahertz range. The other is a nonlinear optical crystal, a material that responds nonlinearly to incident light. Terahertz waves can be emitted by effectively controlling this crystal. Just like electron devices, photonics also has its strengths and weaknesses depending on the materials used, and we are continuing our efforts to generate terahertz waves of the desired frequency.

WATANABE Our laboratory conducts research on electron devices, such as transistors made of compound semiconductors and silicon complementary metal-oxide-semiconductor (CMOS) integrated circuits, also called "high-frequency devices." In contrast to Dr. Sekine's laboratory, we take the approach of first dealing with lower frequencies, and gradually go up to higher frequencies. It is a domain called terahertz electronics. This research also becomes more difficult as the frequencies become higher. The limits are decided by the properties of the semiconductor material. Therefore, we are studying how the materials and technologies should be combined, through trial and error.

——So there are challenges whether you work your way from higher frequencies or from lower frequencies.

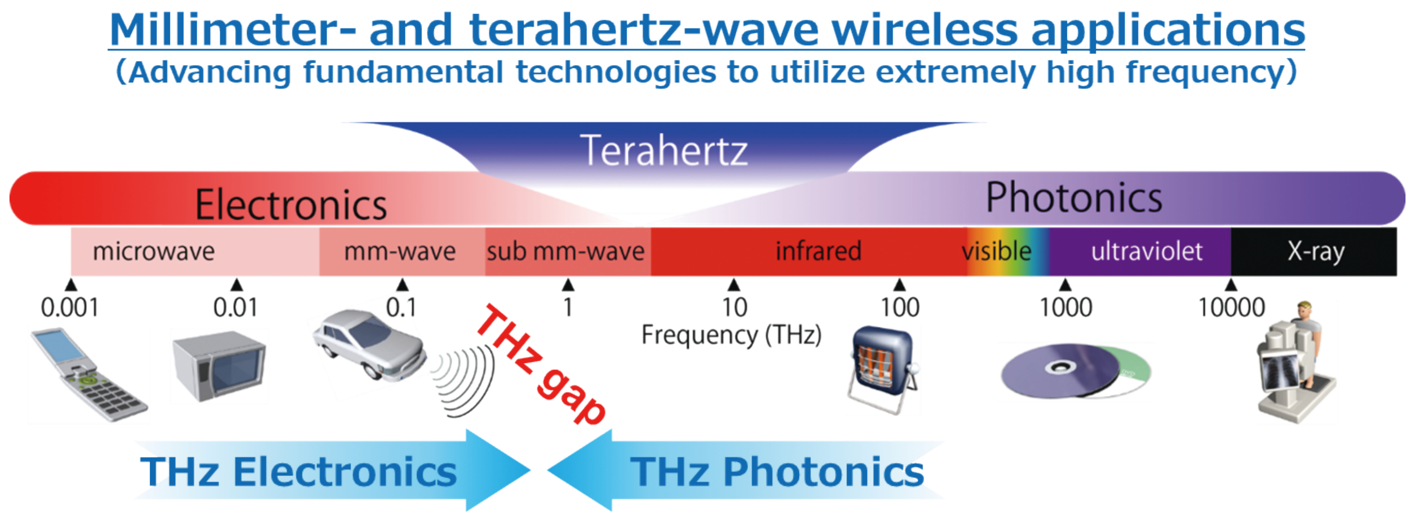
WATANABE There is a range known as a "terahertz gap" between terahertz electronics and terahertz photonics. We think it may be possible to use both electron and optical devices in this boundary region by approaching this region from both sides.

SEKINE Terahertz electronics and terahertz photonics have different strengths, and they have been gradually converging over the past few years. Papers have also been published with reports on the successful generation of 300 GHz or 500 GHz terahertz waves.

Research on such extremely high frequency ranges as terahertz waves is a field with a short history, so there are still many challenges that need to be overcome. As mentioned earlier, information on material properties remains very insufficient, and there is still much room left to study applications in measurement.

Progress in Standardization

——Does anything other than research need to be done to make terahertz waves usable technology?



SEKINE In order to actually use terahertz waves, frequency bands need to be internationally allocated for them. At present, the process of frequency band identification (one step away from allocation) has been completed at the World Radiocommunication Conference (WRC) in 2019, or WRC-19 (use in communications in the 275 to 450 GHz range), but bands have yet to be allocated. Also, studies on specific use cases are only just about to start. However, studies on devices themselves have started moving, and we are gradually carrying out joint work with the system side.

Various Use Cases can be Realized through Ideas

——What kinds of use cases do you have in mind?

SEKINE We are thinking of dedicated short-range communications (DSRC). We are working together with the Social-ICT System Laboratory on technology to cause a large amount of data that has been accumulated in a certain location to be instantly transmitted the moment it passes a point where a transmitter/receiver has been installed. Once information enters the backbone network, which is an ultra-high-capacity optical fiber network, it can be utilized in all kinds of ways.

WATANABE Our laboratory is thinking of a terahertz wireless local area network (LAN), which is like a terahertz waves version of Wi-Fi. Although terahertz waves do not travel far, an ultra-high-speed wireless LAN can be set up in a small room where the waves only need to reach slightly over ten meters at most. I think there are a variety of potential uses, such as real-time video transmission in hospital operating rooms and studios.

SEKINE As terahertz waves basically do not reach far, using them in a beam form makes it easier to avoid interference, and we expect that they can be applied to wireless communications in factories. There are already devices that can produce terahertz waves that travel a hundred and several tens of meters, so I think they can be put to various uses.

WATANABE Both electron and optical devices have their material and physical limitations based on the materials used, but it is possible to realize various systems through ideas. I think if we actively show people what terahertz waves can technically do, it will help them discuss what kinds of use cases there could be.

SEKINE We also pay attention to "digital twins" that make use of high-speed, large-capacity communication technology. In the Cabinet Office's science and technology policy "Society 5.0," cyber-physical spaces (CPSs) are drawing interest. As it will be vital to upload an ultra-large amount of raw data in CPSs, I think it would be beneficial to introduce a terahertz communication network in a wireless system.

In addition, low-latency terahertz communications are expected to play an important role also in the idea of the "City on the Moon" proposed by NICT's Beyond 5G Research and Development Promotion Unit, in which a person can transfer all of their senses to a robot on the moon surface, and can work as if they are actually on the moon through that robot.

Future Prospects

——Please tell us about the future prospects.

SEKINE Research on terahertz waves has been going on for about thirty years now, and individual elementary technologies are improving more and more. Therefore, we would like to achieve social implementation of whatever technologies become usable.

WATANABE I think it is important to show manufacturers and the public how terahertz waves can be used, and to hold thorough discussions. We want to get a lot of people involved, and to increase the number of people who understand the usefulness of terahertz waves.

——Thank you very much for today.

Research and Development of Indium Antimonide Based Transistor Technology

Achieving world's top-level radio-frequency performance

MACHIDA Ryuto

Researcher (Tenure-Track)
Terahertz ICT Device Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute

After completing graduate school, Dr. MACHIDA worked as an Assistant Professor at Tokyo University of Science and as an engineer at Sony Corporation. He joined NICT in 2019. He has been engaged in research and development of crystal growth and transistor fabrication technologies for narrow bandgap semiconductors.
Ph.D. (Engineering).

WATANABE Issei

Director of Terahertz ICT Device Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute

After completing doctoral course, Dr. WATANABE joined NICT in 2004. He has been engaged in research on millimeter- and terahertz-wave compound semiconductor electron devices and MMICs, and high-frequency measurement technologies. He is currently a Visiting Professor at Tokyo University of Science.
Ph.D. (Engineering).

In order to utilize millimeter- and terahertz-wave bands at frequencies of 30 GHz to 3 THz (GHz and THz are 1 billion Hz and 10 trillion Hz, respectively), technologies to fabricate electron devices that operate in these bands are very important. This article introduces the achievements of research and development of indium antimonide (InSb) based transistor technology.

Background

We engage in research and development of electron devices that operate in the terahertz-wave band in the 300 GHz or higher regions toward realizing wireless communication systems of higher speed and larger capacity than current systems. In particular, indium gallium arsenide (InGaAs) and gallium nitride (GaN), which are III-V compound semiconductors, have a high electron saturation velocity, and transistors that use these materials in the channel layer can be expected to operate at high frequencies. While the current-gain cutoff frequency (f_T) and the maximum oscillation frequency (f_{max}) are indicators of radio-frequency (RF) characteristics of transistors, NICT has achieved f_T = 562 GHz (the record f_T in the world as of 2002) in an InGaAs-channel high electron mobility transistor (HEMT) and f_{max} = 287 GHz (the record f_{max} in Japan from 2016 to the present) in a GaN-channel HEMT to date.

In order to achieve higher f_T and f_{max}, we are developing transistors using indium antimonide (InSb) and gallium indium antimonide (GaInSb), which is a mixed crystal semiconductor of InSb and gallium antimonide (GaSb). These are semiconductor materials with a higher saturation velocity than InGaAs and GaN. InSb-based materials, also called "narrow-bandgap semiconductors" due to having a narrower bandgap than InGaAs, GaN, silicon (Si), or gallium arsenide (GaAs), have been actively used in research and development relating to magnetic sensors and infrared sensors, but there have been hardly any reports of research on transistors using InSb-based materials. There are two reasons for this: (1) epitaxial wafers* ("epi-wafers") to be used for fabricating InSb-based transistors are not commercially available, and researchers need to grow higher-quality epi-wafers themselves; and (2) InSb-based materials have low chemical resistance, such as acid or alkali, used in the transistor fabrication process, and are also susceptible to damage during the thermal and plasma process. A major challenge in the development of InSb-based transistors is to minimize these effects and prevent quality degradation of the crystalline semiconductor itself.

Fabrication Process of InSb-based Transistors

NICT started joint research with Tokyo University of Science in 2009 to develop InSb-based transistors. The university's molecular beam epitaxy (MBE) system was used for the crystal growth of InSb-based epi-wafers, and NICT's clean room facility, semiconductor manufacturing equipment, and high-frequency measuring instruments were used to fabricate transistors and evaluate their performance.

The MBE system can control composition and thickness on the order of 0.1 nm (1 nm is one-billionth of 1 m) under ultra-high vacuum (approximately 0.1-trillionth of 1 atmosphere), and it enables crystal growth of a high-quality epi-wafer for transistors (Figure 1). In preparation for InSb-based transistor fabrication, based on the InGaAs-channel HEMT fabrication technologies developed and owned by NICT, each fabrication process of InSb-channel HEMTs was optimized. In particular, we used a silicon oxide (SiO_x) film deposited by a high-vacuum evaporator that plays the following three roles: (i) passivating the surface of the semiconductor material; (ii) improving the adhesion of the resist for electron beam lithography; and (iii) mechanically supporting the nanoscale-gate electrode foot, and succeeded in fabricating an InSb-channel HEMT without plasma-induced damage, unlike general plasma deposition methods (Figure 2).

Figure 1 A 2-inch diameter epi-wafer grown using an MBE system for fabrication of InSb-based transistors.

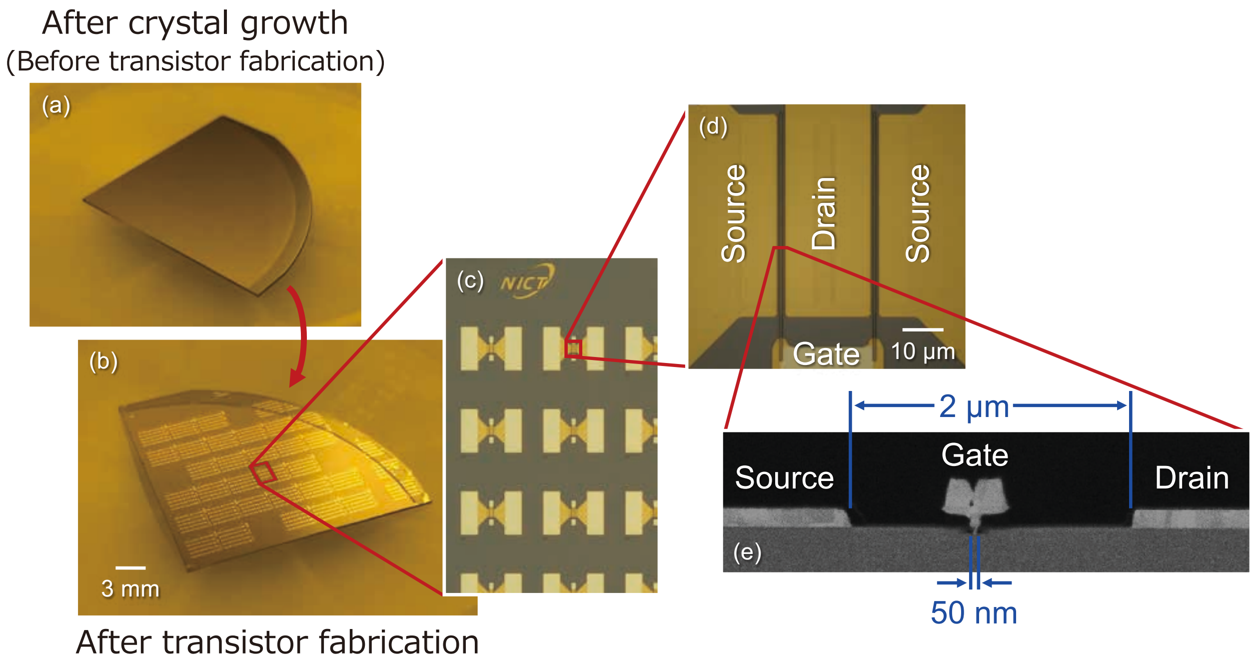


Figure 2 (a) An epi-wafer after crystal growth (before transistor fabrication). (b) The wafer after transistor fabrication. (c) An optical microscopy image of the area with some transistors (HEMTs) arranged. (d) An optical microscopy image of the sources, gate, and drain electrode. (e) A cross-sectional scanning electron microscopy image of a HEMT. The source-to-drain distance and the gate length (L_g) are respectively 2 μm and 50 nm as designed.

Achieving the World's Top-level RF Characteristics in an InSb-based Transistor

In 2016, our research group achieved f_T > 300 GHz for the first time by adopting a SiO_x film formed by the high-vacuum evaporator, and in 2017, achieved f_T = 316 GHz by improving the buffer layer structure and the gate recess process. Moreover, the sheet electron density in the channel layer was increased by changing the channel layer material from InSb to GaInSb, and we succeeded in crystal growth of an epi-wafer with reduced sheet resistance. In 2021, we were able to achieve f_T > 300 GHz also in a GaInSb-channel HEMT by further increasing the sheet electron density by thinning the spacer layer. To achieve even higher RF performance in a GaInSb-channel HEMT, we newly introduced a double-side δ-doped structure, aiming to improve the average electron velocity under the gate electrode through the shortening of the gate-to-channel distance and to compensate and increase the sheet electron density in the channel layer, which decreases as the thinner barrier layer. As a result, we achieved f_T = 342 GHz (gate length L_g = 50 nm), which is equivalent to the record f_T of 340 GHz for an InSb-based transistor, and f_{max} = 451 GHz (L_g = 70 nm), which is also close to the record f_{max} of 480–490 GHz for an InSb-based transistor, and clarified that $f_T \geq$ 300 GHz and $f_{max} \geq$ 400 GHz can simultaneously be achieved for our GaInSb-channel HEMT at $L_g \leq$ 70 nm (Figure 3).

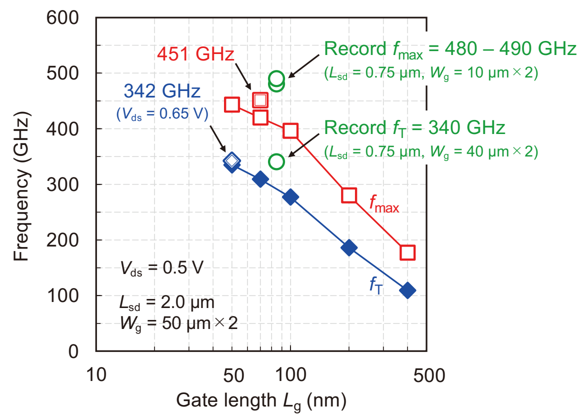


Figure 3 The L_g dependence of the f_T and f_{max} for GaInSb-channel HEMTs. The record f_T and f_{max} for an InSb-based transistor of another research group are indicated for comparison.

Future Prospects

InSb-based semiconductors can be applied not only in transistors that operate in the terahertz-wave band, but also in devices that can receive/emit medium- to long-wavelength infrared light with wavelengths of 3–5 and 8–14 μm (1 μm is one-millionth of 1 m) due to their narrow bandgaps. It is difficult to fabricate a device that receives/emits light of these wavelengths with the bandgaps of InGaAs-based and GaN-based materials, and the high affinity with infrared light receiving/emitting devices is a unique feature to InSb-based transistors. Going forward, we will aim to improve the RF characteristics of (Ga)InSb-channel HEMTs by further improving the crystal growth and transistor fabrication technologies and optimizing the transistor structure. We will also explore the possibility of realizing a photonic-electronic convergence/integrated device that combines a terahertz-wave band transistor and an infrared light receiving/emitting device, using an InSb-based material as a common base.

* A thin slice of crystalline semiconductor, produced by growing a layer structure in accordance with its purpose. Here, it particularly refers to an epi-wafer produced by growing a heterogeneous material layer structure for an InSb-based transistor on a single crystalline semiconductor, such as a GaAs wafer.

Measurement and Evaluation Technologies Required for Research and Development of High-Frequency Devices:

Cryogenic probing measurement and 3D antenna radiation pattern measurement

WATANABE Issei

Director of Terahertz ICT Device Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute

After completing doctoral course, Dr. WATANABE joined NICT in 2004. He has been engaged in research on millimeter- and terahertz-wave compound semiconductor electron devices and MMICs, and high-frequency measurement technologies. He is currently a Visiting Professor at Tokyo University of Science.
Ph.D. (Engineering).

In recent years, electron devices and integrated circuits (ICs) have been fabricated not only on semiconductor materials, such as GaAs, InP, SiC, GaN, and Si, but also on substrates made of various non-semiconductor materials. In addition, as electron devices and ICs now operate at higher frequencies and at higher speeds, it is important to establish high-precision and accurate measurement technologies for evaluating their performances and designing them. This article introduces measurement and evaluation technologies required for research and development of devices that operate at high frequencies, called "high-frequency devices."

Background

NICT is promoting research and development to utilize high-frequency bands that have yet to be sufficiently utilized, such as millimeter- and terahertz-wave bands (frequencies: 30 GHz to 3 THz), as "new radio spectrum/frequency resources." For example, we are working on achieving higher speed and frequency performances in high-frequency devices, such as high electron mobility transistors (HEMTs) that use III-V compound semiconductors InGaAs or GaN for the channel layer, and developing technologies to evaluate their performances. Also, in the fields of wireless communications, sensing, and imaging in microwave band (frequencies: 3 to 30 GHz) and millimeter- and terahertz-wave bands, we are establishing technologies to evaluate the performance of antennas required for transmitting and receiving signals that have been oscillated or amplified by using electron devices.

Measurement of the Performance of High-frequency Device at Cryogenic Temperatures

Electron devices around us operate in a room-temperature environment, but there are also devices that can operate at cryogenic (extremely low) temperatures close to absolute zero (0 K [kelvin], −273°C). At cryogenic temperatures, the lattice vibrations of atoms that constitute an electron device are suppressed to the utmost, so phonon scattering, which is a factor that inhibits the electron (carrier) transport inside the device, becomes smaller. As a result, the noise characteristics improve and the drift velocity of electrons (electron mobility and electron saturation velocity) increases compared to those at room temperature, and the device is expected to demonstrate low noise, high gain, and high sensitivity. Moreover, quantum computers, which have been attracting attention recently, can operate at cryogenic temperatures as they use superconducting devices, so it is essential to evaluate their performance at cryogenic temperatures.

Figure 1 shows a cryogenic DC/RF probing system that can measure the direct-current (DC) characteristics and radio frequency (RF) characteristics of high-frequency devices within a range of room temperature to cryogenic temperatures (300 to 5 K, 23 to −268°C). Generally, when evaluating the DC and RF characteristics, a high-frequency measuring instrument, such as a semiconductor device parameter analyzer or vector network analyzer (VNA), is used, and the measurement is conducted on-wafer by using DC/RF probe needles. For measurement at cryogenic temperatures, the system has a vacuum heat-insulation and cooling chamber (Figure 2) and a vacuum exhaust mechanism, such as a turbomolecular pump, and inside the chamber, there are DC/RF probe needles and a sample holder for setting the devices to be measured. The positions of the probe needles and the sample holder can be controlled from outside the chamber.

When evaluating the RF characteristics of high-frequency devices, the VNA needs to be calibrated before the measurement.

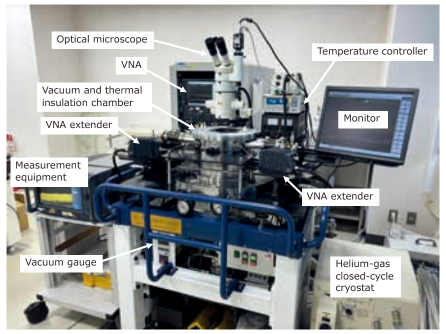


Figure 1 Cryogenic DC/RF probing system (measurement temperatures: 300 to 5 K)

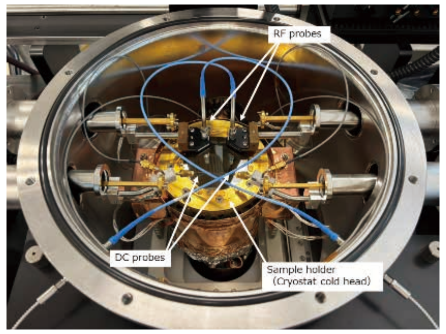


Figure 2 DC/RF probe needles and a sample holder inside a vacuum heat-insulation and cooling chamber

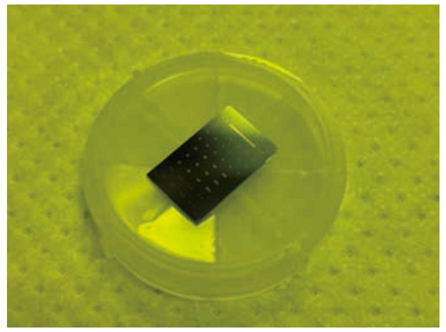


Figure 3 NICT's ISS on an InP substrate that was used for evaluating the RF characteristics at cryogenic temperatures

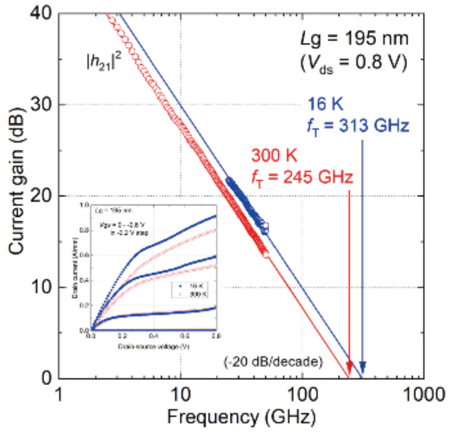


Figure 4 RF characteristics (measurement temperatures: 300 and 16 K) of an InGaAs-channel HEMT on an InP substrate measured by using a cryogenic DC/RF probing system

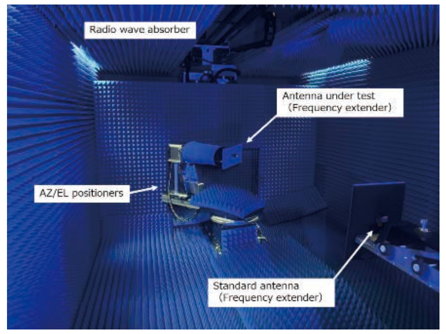


Figure 5 3D antenna radiation pattern measurement system inside a small electromagnetic anechoic chamber

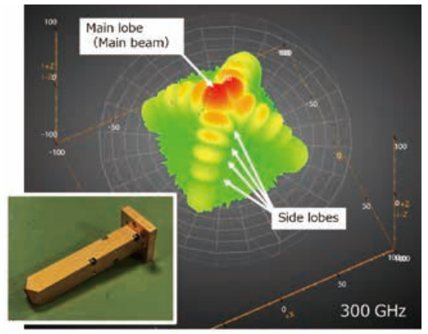


Figure 6 3D radiation pattern (measurement frequency: 300 GHz) of a 220-330 GHz-band pyramidal horn antenna (bottom left)

At room temperature, we use, for example, a 50 Ω resistor on a commercially available impedance standard substrate (ISS), but at cryogenic temperatures, the resistance value of a 50 Ω resistor will no longer be 50 Ω. Therefore, we fabricated an ISS on an InP substrate by using NICT's nano-scale device fabrication technique, as a new standard that indicates accurate 50 Ω (Figure 3). On this ISS, we designed and fabricated a 50 Ω coplanar waveguide (CPW) instead of a 50 Ω resistor, and evaluated the DC and RF characteristics of a HEMT that was cooled to 16 K. Figure 4 shows the RF characteristics of an InGaAs-channel HEMT with a gate length L_g = 195 nm and a gate width W_g = 100 µm fabricated on an InP substrate when biased at a drain-source voltage V_{ds} = 0.8 V. By cooling the HEMT from 300 to 16 K, the drain current increased, and the current-gain cutoff frequency (f_T) at 16 K indicated 313 GHz, which is an approximately 28% enhancement compared to f_T = 245 GHz at room temperature.

Antenna Radiation Pattern Measurement in Millimeter- and Terahertz-wave Bands

Figure 5 shows a three-dimensional (3D) antenna radiation pattern measurement system for evaluating the performance, in particular measuring the gain and radiation directivity, of antennas required for transmitting and receiving signals in millimeter- and terahertz-wave bands. This system is installed inside a small electromagnetic anechoic chamber. By using NICT's VNA and waveguide frequency extenders for 50 to 1,100 GHz (= 1.1 THz), the performance of various antennas can be evaluated in this frequency range. To measure a 3D antenna radiation pattern, the polarization and distance between the transmitting and receiving antennas (2 m at maximum) are to be set, while controlling the azimuth and elevation at high precision.

As an example of measurement using a 3D antenna radiation pattern measurement system, Figure 6 shows a 3D radiation pattern (measurement frequency: 300 GHz) of a 220-330 GHz-band pyramidal horn antenna. This pattern indicates that the main beam (main lobe) with the largest signal strength is in the direction directly in front of the antenna aperture, that it has polarization characteristics, and that there are also multiple extra radiations (side lobes) in the vertical and horizontal polarization directions.

Application of High-frequency Device Measurement and Evaluation Technologies

As high-frequency devices are used in wireless communications, sensing, and imaging not only in millimeter- and terahertz-wave bands, but also in microwave band, research and development is constantly carried out to improve the performance as well as to increase their functions, and the items to be measured and evaluated in high-frequency devices are also considered to be diverse. The measurement and evaluation technologies introduced in this article are expected to be utilized for evaluating the performance of a multiple-input and multiple-output (MIMO) smart antenna and for measuring the dielectric material constant of antenna radome, etc., and also utilized for evaluating the characteristics of future circuit devices for quantum computers.

Fabrication and Stabilization Techniques of Integrated Microcombs

FURUSAWA Kentaro

Senior Researcher, Terahertz Laboratory, Terahertz Technology Research Center, Beyond 5G Research and Development Promotion Unit

After getting his Ph.D on research into microstructured optical fibers, Dr. FURUSAWA studied attosecond physics, nanophotonics and spectroscopy at RIKEN, Canon Inc. and Tohoku University prior to joining to NICT. He has been primarily working on fabrication of integrated photonic devices and ion traps. Ph.D (Engineering).

TETSUMOTO Tomohiro

Senior Researcher, Terahertz Laboratory, Terahertz Technology Research Center, Beyond 5G Research and Development Promotion Unit

Dr. TETSUMOTO joined NICT in 2021 after working at IMRA America Inc. He has engaged in research on integrated photonics, nonlinear optics, and low phase noise terahertz-wave generation. Ph.D. (Engineering).

NICT conducts research on microcombs as a means of generating reference signals in terahertz frequencies, useful for wireless communications as well as high-sensitivity measurements. If microcombs with low power consumption and excellent frequency stability can be supplied at low cost, they can be used, for instance, to increase the efficiency and speed of the wireless communications in the sub-terahertz (0.1 to 1 THz) frequency bands, which are highly anticipated in Beyond 5G / 6G. They can also be important devices for realizing accurate time synchronization between remote communication terminals in optical communication networks.

Technical Challenges Facing Microcombs

A microcomb is an optical frequency comb that is generated by using the nonlinear optical effects in an optical microresonator. Although the nonlinear effects are very weak, in general, they become relevant when the light intensity is high enough. Generation of the frequency comb spectrum, which consists of many spectral lines equally spaced along the optical frequency axis, relies on these nonlinear optical effects, by which energy exchange between the different colors of light occurs.

The optical frequency comb is the technology that contributed to Nobel Prizes in Physics in 2005, 2018, and 2023. In the past, high-intensity electric fields created by ultra-short optical pulses compressed to the order of femtoseconds were required for an optical frequency comb. Since around 2000, the fabrication technology to produce small optical resonators with extremely high Q factors[*1] has been developed. They are typically fabricated on tiny semiconductor chips with dimensions of a few millimeters square. In a high Q resonator, continuous-wave light circulates many times after entering, giving rise to a high-intensity electric field inside the resonator. In other words, as many photons are continuously sent into the resonator, they accumulate inside the resonator. As a result, a high-intensity electric field, with which the nonlinear optical effects are efficiently induced, is built up (Figure 1).

A microcomb is not merely a substitute for conventional counterparts with smaller dimensions, but can also allow us to obtain the frequency spacing with a few hundred GHz (which is rather difficult to realize using the conventional ones). This means that, when the beat signals (“beats” resulting from interference between light with different frequencies) of such a microcomb are detected by using a fast photodiode, electric signals at the same frequency can be generated. In addition, some studies have shown that these signals exhibit low noise characteristics that surpass those of signals generated by conventional electronic devices.

Fabrication of Integrated Microcomb Devices

Research and development of photonic integrated circuits (PICs) has remarkably advanced over the past 30 years. In particular, silicon PICs, which use silicon as a waveguide layer, can inherit the existing device processing tools and technologies that have been developed for semiconductor electronic integrated circuits, and are therefore suitable for mass production. For example, they are used in optical transceivers in data centers and contribute to enhancing the functions while reducing the power consumption. We fabricate high-Q optical microresonators using silicon nitride, which serves as a core layer and is a suitable material for high-Q optical resonators (Figure 2). It also has high affinity with silicon photonics. When fabricating semiconductor devices, in general, three-dimensional device structures are created by repeating processes such as film deposition, mask patterning by lithography, and dry etching to transfer the mask pattern to the film. In the case of photonic devices, such as low-loss waveguides or high-Q resonators, while the structural dimensions are relatively large compared to the electronic counterparts, the device structures need to be extremely smooth in shape (the order of nanometers (one-millionth of 1 mm)) to reduce the scattering loss of light at interfaces with refractive index discontinuities (e.g., between the core and the cladding). This requirement poses another fabrication challenge different from those of electronic devices. Besides, since the thickness of each layer constituting the device structures often reach several microns (several tens to 1,000 times that of an electron device), careful process designs also need to be implemented by accounting for the distortion of the substrate caused by the film stress. NICT has been studying the fabrication processes to realize high-Q resonators while making them simpler by using low-stress silicon nitride films formed by a unique deposition tool, referred to as hot-wire CVD.

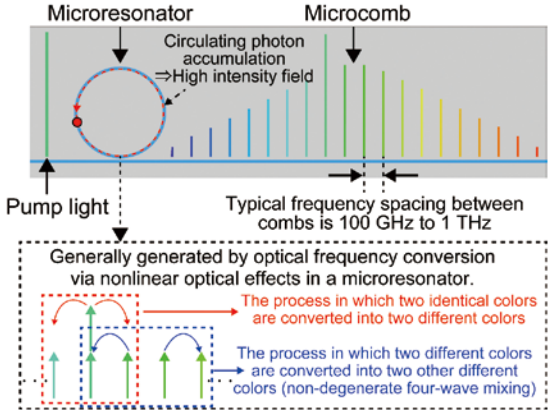


Figure1 Schematic of the principle of microcomb generation

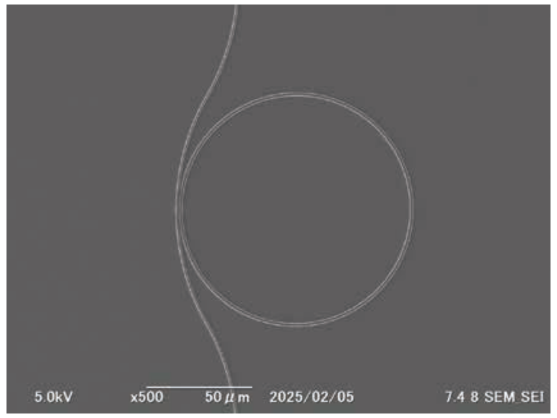


Figure2 Electron microscope image of a silicon nitride ring resonator

Stabilization of Integrated Microcombs

The oscillation frequency of an oscillator used for generating wireless communication signals, etc. is not temporally constant, due to thermal and mechanical fluctuations, but in order to ensure stable communications between different equipment, there is a need to align the frequencies referenced by each equipment. The synchronization of the reference frequencies between equipment is also important for synchronizing time, which is derived from the reciprocal of frequency. Therefore, frequency synchronization between oscillators is conducted by using phase-locked loops, etc. “Stabilization of a microcomb” refers to synchronization of the optical frequencies of the comb lines of the microcomb or the frequency differences between the comb lines (frequencies that can be extracted as radio signals) with a stable frequency standard. In particular, an optical stabilization technique called “optical frequency division,” which effectively uses the characteristics of the optical frequency comb, can substantially suppress frequency fluctuations (phase noise) between comb lines and can be utilized to generate ultra-low phase noise terahertz waves. NICT is working to develop techniques for achieving a low-noise microcomb, as well as techniques for realizing stabilization in an easier and more scalable manner.

One of such techniques is the stabilization of microcombs by light injection. Figure 3 shows the measurement result of phase noise when reference light of two wavelengths is injected into a microcomb. It indicates that the microcomb noise after the injection overlaps well with the reference noise. This is because the gain of the nonlinear optical effect becomes high in the two injected wavelengths, and the comb line wavelengths of the microcomb are pulled toward the two injected wavelengths. We consider that it is possible to synchronize multiple microcombs with the same reference signals in a simplified manner by repeatedly using this process.

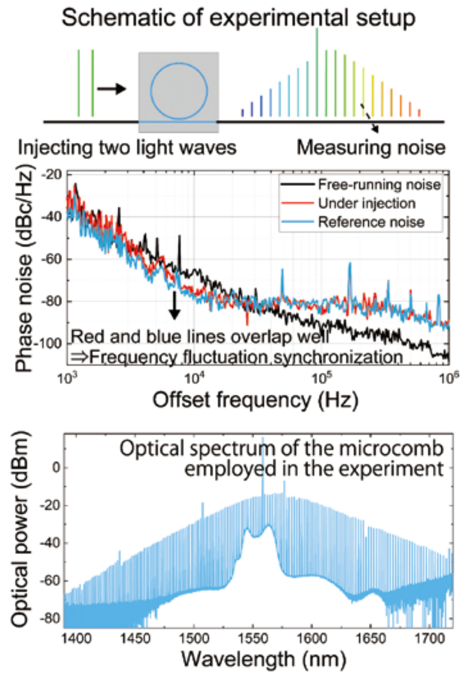


Figure3 Injection locking experiment of a microcomb

Future Prospects

Microcombs have the potential to dramatically improve the precision of the time and frequencies that can be used in real life, and as a result, improvements are expected in communication stability and measurement precision of positions, etc. One of the technical challenges of microcombs is the integration of elementary technologies on a chip level. However, over the past three years or so, microcomb generation using a chip, on which a laser and an optical microresonator are integrated, and its applications have been demonstrated on a research level, followed by the emergence of foundries[*2] that provide the chips on which these multiple components are integrated. In addition, some deep tech ventures have developed small optical clocks (clocks that reference the frequency of atomic transition in the optical band) using microcombs, and their use in positioning with more than one-digit higher positional precision and a wider coverage area than what is currently available using the global positioning system (GPS) is being studied. NICT also will exert itself toward realizing a future in which higher-precision frequencies can be easily utilized as social infrastructure.

*1 A performance index for optical resonators. The higher the Q factor, the lower the loss and the longer the photon resides inside the resonator.

*2 They originally referred to semiconductor chip manufacturing plants, but here they refer to manufacturing-specialized companies that manufacture semiconductor chips on consignment.

Recent Research on Quantum Cascade Lasers

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Dr. YASUDA joined NICT in 1997 after working at Toshiba corporation. He has engaged in research and development of millimeter-wave and terahertz semiconductor devices.
Ph.D. (Engineering).

A quantum cascade laser (QCL) is a semiconductor laser that emits light in the terahertz band to the mid-infrared range. Terahertz QCLs (THz-QCLs) are anticipated to be used in high-speed, large-capacity wireless communications, etc. However, room-temperature operation of THz-QCLs has yet to be realized, and their performance needs to be further improved. We considered improving performance by using material systems that differ from the conventional GaAs material system,*1 and as its first step, we are conducting research and development to grow QCL structures of the InGaSb material system*2 with uniformity and few defects for achieving laser oscillation.

Background

The frequency regions of the sub-terahertz band (0.1 to 1 THz) and terahertz band (1 to 10 THz) are expected to be used in large-capacity wireless communications, spectroscopic measurement, imaging measurement, etc. In order for these frequency regions to be widely used in reality, there is a need for small, high-output semiconductor signal sources that can operate at room temperature. While research and development of electron devices, such as transistors, is making progress in the sub-terahertz band, a sufficient output has yet to be achieved around 1 THz. Meanwhile, research and development of optical devices, such as QCLs, has been conducted in the terahertz band. THz-QCLs can produce high output power, but as they need to be cooled with liquid nitrogen, etc., improvement of the operating temperature poses a challenge.

The operating principle of a THz-QCL is explained by using Figure 1. In a QCL, a semiconductor multiple-quantum-well structure consisting of quantum wells and barriers (consisting of three quantum wells and three barriers in Figure 1) is repeated several times and appropriate voltages are applied on both ends. Electrons in subband level 2 in Figure 1 are scattered to subband level 1 by lattice vibrations called "longitudinal optical (LO) phonon." These electrons are injected to subband level 3 of the next period by a resonant tunneling effect. As a result, the number of electrons in subband level 3 becomes larger than that in subband level 2, forming population inversion,*3 and light (electromagnetic waves) is emitted when electrons transit between subband levels 3 and 2, realizing laser oscillation. The frequency of a laser is determined by the energy difference between upper laser level 3 and lower laser level 2.

In conventional THz-QCLs, GaAs was used for quantum wells and AlGaAs*4 was used for barriers, as a material system. The highest operating temperature of 261 K (frequency: 4 THz) was reported by using this GaAs material system. However, this was only pulse operation, and room-temperature operation and continuous-wave oscillation remain as challenges.

Crystal Growth of InGaSb Terahertz Quantum Cascade Laser Structures

One possible means to further improve the performance of THz-QCLs is to use a material system that differs from the GaAs system, such as the GaN system or the GaSb system. Physical property values, such as LO phonon energy and effective electron mass, change according to the material system. As mentioned earlier, the LO phonon scattering moves electrons from lower laser level 2 to level 1 and plays the role of increasing the population inversion. However, if the temperature rises, LO phonon scattering from upper laser level 3 to lower laser level 2 also occurs, and the population inversion decreases. In addition, LO phonon scattering also affects the broadening of laser levels. If the effective electron masses differ, the thickness of one period will have to be changed, so the electric field strength will change and the impact of the roughness of the interfaces between quantum wells and barriers on performance will also vary. As shown in Figure 2, all material systems have their strengths and weaknesses. Thus, we performed an electron transport simulation of QCLs by using the non-equilibrium Green's function method that quantum-mechanically incorporates the interaction between electrons and lattice vibrations, etc. We calculated the optical gain, and obtained the result that the GaSb system is the best among the three. However, we found that, in GaSb, the energy difference between the Γ valley and the L valley is only 84 meV, and if it is used in a QCL, there will be few electrons in the Γ valley at room temperature. As the energy difference between the valleys will be sufficiently large in InGaSb with the In ratio of approx. 0.2 or more, we decided to use InGaSb instead of GaSb for quantum wells. In the simulation, the gain improved over that of the GaAs system, even by using InGaSb. Therefore, we decided to grow a THz-QCL structure using InGaSb for quantum wells and AlInGaSb for barriers by employing molecular beam epitaxy (MBE).*5

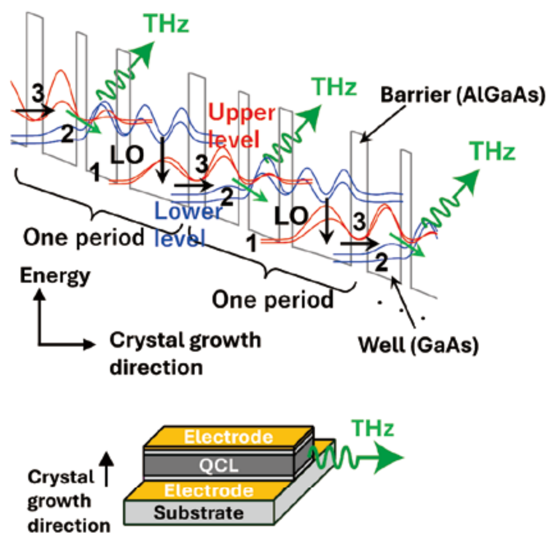

Figure 1 Subband structure in the conduction band of a THz-QCL

Material system	LO phonon energy [meV]	Effective electron mass [m₀]	Thermally activated LO phonon scattering	Broadening of laser levels	Electric field strength
GaAs	36	0.063	Mid	Mid	Mid
GaN	92	0.2	Low	High	High
GaSb	30	0.041	High	Low	Low

★ Lower indicates better QCL performance

Figure 2 Characteristics of THz-QCLs fabricated with various material systems

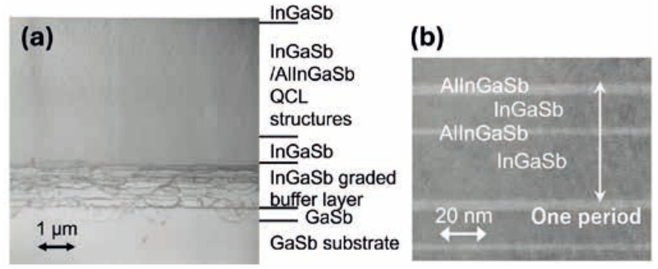

Figure 3 Cross-sectional TEM images of an InGaSb/AlInGaSb THz-QCL structure3 (a) Overall, (b) One period of the QCL

In growing an InGaSb THz-QCL structure, there is a problem of a lack of a semiconductor substrate that can be lattice-matched to InGaSb. Thus, we grew an InGaSb composition graded buffer layer in which the In ratio was gradually and continuously increased from nearly 0, on a GaSb substrate, and grew an InGaSb layer above it. We optimized the substrate temperature and paid attention so that no oxygen-related impurities would be generated on the substrate. After that, we selected the Al ratio and In ratio of AlInGaSb so that it is lattice-matched to InGaSb, and grew a THz-QCL structure with a thickness of 3 μm. In the case of a 3 μm-thick THz-QCL structure, we grew the structure by repeating a QCL structure with a period thickness of about 50 nm 60 times. Meanwhile, in order to achieve THz-QCL oscillation, the QCL region needs to have a thickness of about 10 μm.

Figure 3 shows cross-sectional transmission electron microscopy (TEM) images of QCL structures grown by MBE. When observed in a wide area, high-density dislocations were found in the InGaSb composition graded buffer layer, but hardly any threading dislocations were confirmed in the InGaSb layer above it.

The threading dislocation density in the THz-QCL region was about 1 × 10^7 / cm^2 irrespective of the thickness of the QCL region. When one period is magnified, the layers for one period were almost uniform, and the interfaces were flat. In the future, we will aim to grow an even thicker, high-quality QCL region and oscillate a THz-QCL.

Performance Improvement of Mid-infrared Quantum Cascade Lasers

An operation simulation using the non-equilibrium Green's function method can also be performed for a mid-infrared QCL. High output and room-temperature operation have already been realized for mid-infrared QCLs, and they are being used in fields such as trace gas analysis and remote sensing. Ammonia, which has been an important chemical substance as a raw material for fertilizers, is expected to become widely used as a carrier of hydrogen, a future energy source. As ammonia gas absorbs infrared radiation with a wavelength of 10 μm, the ammonia gas concentration in the air can be identified by emitting infrared radiation with a wavelength of 10 μm from a QCL, passing it through the gas to be measured, and detecting it by using a light receiver. We performed a simulation of a 10 μm-band QCL using InGaAs for quantum wells and InAlAs for barriers by employing the non-equilibrium Green's function method, and, in particular, optimized a structure that depopulates electrons from a lower laser level. As a result, we succeeded in more than doubling the output power and reducing the power consumption as compared to conventionally used structures.

Future Prospects

We are attempting to grow a QCL region with few defects and a thickness of about 10 μm toward oscillation of InGaSb THz-QCLs. We consider that the use of the terahertz frequency region will progress significantly if room-temperature operation of THz-QCLs is realized.

*1 A semiconductor material system based on GaAs. GaAs is used for quantum wells, and AlGaAs is used for barriers.
*2 A material system in which InGaSb is used for quantum wells and AlInGaSb is used for barriers.
*3 A state in which the number of electrons that exist at a higher energy level is larger than that at a lower energy level. This state is required for laser oscillation.
*4 Aluminum gallium arsenide. The composition formula is $Al_xGa_{1-x}As$ (0 < x < 1)
*5 Molecular beams are irradiated onto a substrate surface in high vacuum, and a crystal with a certain orientation relationship with the substrate is built up.

Resonant Tunneling Diodes for Next Generation Ultra-fast Wireless Communication

Cito Michele

Researcher,
Terahertz ICT Device Laboratory,
Koganei Frontier Research Center,
Advanced ICT Research Institute,
Ph.D. (Engineering)

Biography

1991	Born in Italy
2018	Graduate from Polytechnic school of Bari (Italy)
2022	Completed the Ph.D. from University of Glasgow (UK)
2023	Joined NICT

Q&As

Q What is good about being a researcher?

A Science gives you unlimited opportunities to explore, understand, and improve the world.

Q What advice would you like to pass on to people aspiring to be researchers?

A Science and technical studies provide the foundation for research, but creativity and imagination are key to innovation. Look for opportunities, big or small, to travel, explore hobbies, enjoy the arts, and connect with nature whenever you can.

Q What are you currently interested in outside of your research?

A I am immersing myself in Japanese culture (food, traditions, martial art, etc). I like visiting temples and shrines and taking pictures of the cats I found.

We can think of wireless networks like highways, and data as the cars traveling on them. Just like highways can get crowded during rush hour, today's wireless networks are becoming overwhelmed by the huge amount of data we use every day (social media, gaming, IoT devices, etc). My research is about creating faster and wider "data highways" using a technology called terahertz (THz).

Terahertz waves are like adding many extra lanes to a highway and putting race cars instead of ordinary cars: they can carry a lot more data, much faster than the technology we use now.

To realize this, I work with a special kind of device called Resonant Tunnelling Diode (RTD), a nanometric electron device that can generate terahertz waves and can be used to build these new types of data "highways." The generation of terahertz waves is difficult because advanced materials are required. Inside these materials, tiny "particles" called electrons (e^-) are moving and they are fundamentals for the device operation. You can think of electrons as people trying to across a crowded room. Sometimes, they bump into each other or into parts of the furniture. When this happens, they lose speed/energy, and these losses make it harder for the RTDs to work efficiently.

My task is to improve the materials and the RTDs design so the electrons can move more smoothly, without "hurting" each other or other obstacles. By minimizing losses, the devices can generate stronger and more stable terahertz waves. This can change how we make streaming, gaming, and change our everyday life. It could also help in other areas, like medical imaging and security systems.

By building these new data highways, we can make communication smoother and faster, helping us keep up with the growing need for speed in our digital world.

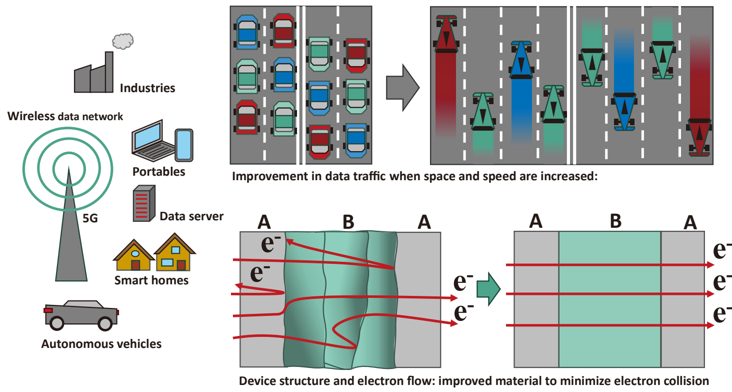

Figure Schematic of the research scenario: Wireless data applications (left), enhanced "data highway" for speed and capacity (top), and improved material quality to reduce electron collisions (bottom).

Entrepreneurs Gathering from Around the Nation at the "Entrepreneurs' Koshien" and the "Entrepreneurs' Expo"! The Allure of Regional ICT Startups that Pursue Further Evolution

Entrepreneur Promotion Office,
ICT Deployment and Industry Promotion Department

The Entrepreneur Promotion Office and the Ministry of Internal Affairs and Communications jointly implement the "National Accelerator Program," which provides support for the discovery and incubation of next-generation ICT human resources, such as students aspiring to conduct business that utilizes ICT, and the business expansion of regional ICT startups, with the aim of solving regional issues and revitalizing the economy through the creation of regional ICT startups.

Along with ICT mentors, including venture capitalists, we look for promising entrepreneurs and future entrepreneurs at collaborative events held by "Entrepreneur Supporters"* in each region, and help them brush up their business plans through mentoring sessions with the ICT mentors. As opportunities for them to present their refined business plans, we hold the "Entrepreneurs' Koshien" (for students) and the "Entrepreneurs' Expo" (for young entrepreneurs). In FY2024, these events were held at Marunouchi Building Hall & Conference Square on March 13 and 14, 2025, with 110 people concerned participating in the "Entrepreneurs' Koshien" and 103 people in the "Entrepreneurs' Expo." Also, many people watched these events via live streaming.

The "Entrepreneurs' Koshien" marked its 14th year and the "Entrepreneurs' Expo" its 23rd year. Awards including the Minister for Internal Affairs and Communications Award, NICT President's Award (see the table), and Partner Company Special Award are granted to excellent presenters at these events. This fiscal year, many business plans involved themes in the life science field, focusing on dementia or quality of life (QOL) for example. In regard to technology, there were also many business plans born from deep tech, such as sensors, robots, and AI.

Participants in the Entrepreneurs' Koshien commented, "Thanks to the mentoring, I've been able to greatly improve my business plan and achieve significant personal growth," "The mentors provided me with close support, and I was able to learn about various things, such as products and marketing," and "I became more motivated to start business as a result of connecting with fellow participants that tread similar paths as well as organizations and individuals who support us in starting business." Their comments indicate that this event has supported them in increasing their learning and personal growth, and provided a good opportunity for them to enhance their motivation to start business and to think about the future.

Participants in the Entrepreneurs' Expo remarked, "The business speed of other companies inspired us," "It was a great opportunity to expand our network," "It led to improvement of our performance, recognition, and credibility," and "The precise mentoring provided our company with an extremely valuable opportunity to take another look at our business." These remarks suggest that this event has provided a chance for the participants to further brush up their business plans and contributed to the growth and business development of each company.

Some viewers stated, "I was able to learn about the efforts of students," "The presentation contents were extremely high-level and impressive to watch," "I was able to learn about influential domestic startups involved in ICT," and "The Entrepreneurs' Expo has grown dramatically, and the presentations seem to have become more compelling; I also hope to see global expansion and the solving of regional issues in the future."

Hereafter, we will provide commercialization support to the participants by such means as providing opportunities to exhibit their products at large exhibitions.

The Entrepreneur Promotion Office will continue to strengthen the support framework for startups and promote the creation of regional ICT innovation ecosystems through further collaboration with local governments and organizations in each region.

Please see the URL below for information on NICT's support to startups.

https://www.nict.go.jp/venture/ (in Japanese)

* Entrepreneur Supporters: Individuals and organizations that plan and operate collaborative events in various regions and play a central role in the startup community of the respective regions for implementing initiatives toward forming a startup ecosystem there.

Table: FY2024 Minister for Internal Affairs and Communications Awards and NICT President's Awards

	Entrepreneurs' Koshien (Thursday, March 13, 2025)	Entrepreneurs' Expo (Friday, March 14, 2025)
Minister for Internal Affairs and Communications Award	"In-orbit demonstration service utilizing nanosatellites" (Kick Space Technologies / Kyushu Institute of Technology)	"'TriOrb BASE,' a 360° spherical mobility platform that creates the basis for next-generation industry" (TriOrb Inc.)
NICT President's Award	"Easy operation for anyone through haptics! A general-purpose robot changing the fishing industry" (Real Touch / Graduate School of Hokkaido University)	"Development of the Robotic Microsurgery Assistance System (RAMS) that contributes to improving QOL." (F.MED Co., Ltd.)

Participants in the Entrepreneurs' Koshien. At the center of the front row are the winners of the Minister for Internal Affairs and Communications Award and the NICT President's Award

Winner of the Minister for Internal Affairs and Communications Award at the Entrepreneurs' Expo (center), KAWASAKI Hideto, Parliamentary Vice-Minister for Internal Affairs and Communications (left), and the winner of the Best ICT Mentor Award (right)

NICT NEWS 2025 No.3 Vol.511
Published by **Public Relations Department, National Institute of Information and Communications Technology**
Issue date: May 2025 (bimonthly)

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ISSN 2187-4050 (Online)